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March 29, 1963

Office of Naval Research
Power Branch (Code 426)
Room 2509, T-3 Building
Department of the Navy
Washington 25, D. C.

Attention: Dr. Ralph Roberts

Subject: Quarterly Technical Report No. 7
"Experiments for the Measurement of the Acoustic Impedance of a
Burning Solid Propellant"

Reference: Contract No. Nonr 3473 (00)
ARPA Order 23-61

Gentlemen:

Enclosed are two copies of Quarterly Technical Report No. 7 which summarizes
the studies conducted under Contract Nonr 3473 (00) during the period November 15,
1962, through February 15, 1963.

Distribution of this report has been made in accordance with the listings provided
by the Office of Naval Research.

Very truly yours,

THIOKOL CHEMICAL CORPORATION
ELKTON DIVISION

H. G. Jones
H. G. Jones
General Manager

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Enclosure: Quarterly Technical Report No. 7, 2 copies

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QUARTERLY TECHNICAL REPORT NO. 7 - "EXPERIMENTS FOR THE
MEASUREMENT OF THE ACOUSTIC IMPEDANCE OF A BURNING SOLID
PROPELLANT" - CONTRACT NO. NONR 3473 (00)

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THIOKOL CHEMICAL CORPORATION
ELKTON DIVISION
ELKTON, MARYLAND

"EXPERIMENTS FOR THE MEASUREMENT OF THE
ACOUSTIC IMPEDANCE OF A BURNING SOLID PROPELLANT"

QUARTERLY TECHNICAL REPORT NUMBER 7

NOVEMBER 15, 1962, THROUGH FEBRUARY 15, 1963

PREPARED FOR:

OFFICE OF NAVAL RESEARCH
POWER BRANCH, CODE 426
DEPARTMENT OF THE NAVY
WASHINGTON 25, D. C.

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H. G. Jones
General Manager

TABLE OF CONTENTS

	<u>PAGE</u>
ABSTRACT	ii
I. INTRODUCTION	1
II. TECHNICAL PROGRAM	2
A. Passive Tests to Improve Calculation Method	2
B. Experimental Basis and Method of Calculation	6
C. Application of Method to Burning Propellant	11
III. SUMMARY	17
IV. FUTURE WORK	18
V. NOMENCLATURE	19
VI. REFERENCES	20

ABSTRACT

In this report progress of work during the seventh quarter of a program to measure the acoustic impedance of a burning solid propellant surface is described. The method of calculation used for obtaining impedance from measurements made in both solid and vented chambers has been revised to make correction for source impedance in the former case, and to use an analogous method which corrects for both source and hole or vent impedance in the vented chamber. This has resulted in a simplified calculation method which has been tested at 1 atmosphere and at 200 psi and in the frequency range .2-1.0 kc to demonstrate that measurements on passive samples can be obtained in the vented chamber. Tests on a fiber glass pad sample have shown sufficiently good agreement between measurements in solid and vented chambers to indicate that the method is satisfactory for present needs.

The technique used for active shot measurements has been improved by increasing the injected sound intensity and by modifying the driver so that it is not jammed by the pressure surge which accompanies combustion. The combustion noise remains a serious obstacle to obtaining the required acoustic information during the propellant burning interval, and tests are being made to overcome this interference by the use of narrower band pass filters.

I. INTRODUCTION

This work is concerned with measurement of the acoustic impedance of a burning propellant surface. A method developed by O. K. Mawardi for measurement of the impedance of inert sound absorbing materials is being used with modifications that are needed to cope with the special conditions involved in tests made on propellant burning under pressure.

The exhaust ports needed for tests on propellant alter the acoustic response of the chamber and require changes in the method of calculation used on data from a vented chamber. In previous work on this program various methods of calculation which were developed have failed to consistently yield satisfactory results for impedances of inert samples measured in the vented chamber. This problem has been further considered, and work during this period has resulted in a much improved and simplified calculation method.

Further progress has been made in overcoming experimental difficulties which have heretofore prevented the actual attainment of acoustic impedances of burning propellant by this method.

II. TECHNICAL PROGRAM

A. Passive Tests to Improve Calculation Method

In the previous quarterly report¹ a method for treatment of data obtained from measurements of impedance by the Mawardi Method was developed and tested. The method was based on the assumption that source impedance could be neglected in measurements both at 1 atmosphere and at elevated pressures. A considerable simplification in the equations needed for calculations over those previously proposed² was thus effected; but, a careful test of these new equations showed them to be inadequate. Testing was done by making measurements on a perforated metal plate in both the solid and vented chambers. It was assumed that the values obtained in the solid chamber were correct, since the Mawardi method is designed for these conditions; and the ability to obtain concordant values from measurements made under the same conditions in the vented chamber was used as a criterion for correctness of the calculation method.

In general, poor agreement was obtained between the solid and vented body measurements, particularly at elevated pressures, where negative real parts of the acoustic impedance ratios were frequently observed, in both solid and vented chambers. This lack of agreement was ascribed to the fact that the source impedance, under the conditions of our measurements is not sufficiently large to be neglected. Modifications of the equation used for calculations were thus shown to be necessary and were made as described as follows.

1. Measurements in the Solid Chamber

For measurement of an unknown impedance, Z_m , under conditions where the source and microphone impedance are not sufficiently large to be neglected, the following equation has been shown to be applicable.³

$$Z_m = Z_1 \left[\frac{1}{\xi e^{j\theta} - 1} \right] \left[\frac{1}{1 + \frac{Z_1}{Z_0}} \right] \quad (1)$$

$$\xi = E_1 - E_2 \quad \theta = \theta_1 - \theta_2$$

where E_1 and θ_1 = microphone voltage and phase angle, respectively; with rigid termination, and E_2 and θ_2 = microphone voltage and phase angle with sample termination.

Z_1 = impedance of the empty chamber

Z_0 = source impedance

The determination of source impedance is carried out by comparison of voltage and phase angle measurements, both with rigid termination, in two otherwise identical chambers of different volume. Under these conditions, it was previously shown¹ that:

$$\frac{Z_0 + Z_2}{Z_0 + Z_1} = \xi e^{j\theta} \frac{V_1}{V_2} \quad (2)$$

where V_1 is the volume of the smaller chamber whose impedance is Z_1 and V_2 the volume of the larger chamber whose impedance is Z_2 . Chambers whose volumes are 20 and 40 cubic centimeters (cc) have been used for these measurements to

determine Z_0^* .

For each chamber $Z = \frac{\gamma P_1}{2 \pi f v}$, hence $\frac{Z_1}{Z_2} = \frac{V_2}{V_1}$

$$\frac{V_1}{V_2} = \frac{1}{2}, \text{ hence } Z_1 = 2Z_2$$

Substituting in (2) gives:

$$\frac{2Z_0 + Z_1}{Z_0 + Z_1} = \xi e^{j\theta} \quad (3)$$

or

$$\frac{Z_0}{Z_1} = \frac{1 - \xi e^{j\theta}}{\xi e^{j\theta} - 2} \quad (4)$$

The expression is mathematically equivalent to the equation for $\frac{Z_0}{Z_1}$ given by Mawardi⁵, namely

$$Z_0 = Z_1 \frac{\alpha - 1}{\xi \alpha e^{j\theta} - 1} \quad (5)$$

$$\text{where } \alpha = \frac{V_1}{V_2}.$$

The correction term $\frac{1}{1 + \frac{Z_1}{Z_0}} \frac{\frac{Z_0}{Z_1}}{\frac{Z_0}{Z_1} + 1}$ is desired as a numerical

correction term of the form $s + tj$.

* In earlier work on this program, chambers of 20 and 60cc were used. The 40cc chamber was chosen as preferable to the 60cc chamber because the latter does not give the required uniformity of pressure distribution at frequencies above 200 cycles.

$$\text{Let } \xi e^{j\theta} = \xi \cos \theta + j \xi \sin \theta = a + bj \quad (6)$$

$$\text{where } a = \xi \cos \theta \quad \text{and} \quad b = \xi \sin \theta.$$

Using equation (4) and these symbols:

$$\frac{\frac{Z_0}{Z_1}}{\frac{Z_0}{Z_1} + 1} = \frac{\frac{(1-a)-bj}{(a-2)+bj}}{\frac{(1-a)-bj}{(a-2)+bj} + \frac{(a-2)+bj}{(a-2)+bj}}$$

Simplifying gives:

$$s + tj = (a - 1) + bj$$

$$\text{hence } s = a - 1 = \xi \cos \theta - 1 \quad (7)$$

$$t = b = \xi \sin \theta \quad (8)$$

By using the relationships given in equations (7) and (8), the correction terms needed for the source impedance correction term in equation (1) can be readily determined from the ξ and θ values obtained from measurements on the two different chamber volumes.

Using the relationship given in (6) and the s and t correction terms for source impedance, equation (1) can be converted into the working equations needed for calculation of sample impedances from measurements involving comparison of rigid and sample termination conditions in the chamber. These are:

$$R_M = \frac{d [s \xi \sin \theta - t (\xi \cos \theta - 1)]}{\xi^2 + 1 - 2 \xi \cos \theta} \quad (9)$$

$$X_m = \frac{d [s (\xi \cos \theta - 1) + t \xi \sin \theta]}{\xi^2 + 1 - 2 \xi \cos \theta} \quad (10)$$

$$d = \frac{Z_1 A}{c}$$

$$Z_1 = \frac{\gamma P_1}{2\pi f V_1}$$

2. Measurements in the Vented Chamber

In previous work on this program, correction terms for the acoustic effects of the exhaust ports in the vented chamber have been based on comparison of measurements of solid and vented chambers of the same volume, both with rigid termination, as described in a previous report⁴. Calculations using these terms on vented chamber measurements have heretofore failed to give agreement with measurements made in the solid chamber. The neglect of source impedance in these calculations may also have contributed to the failure to obtain agreement.

An alternative approach, which has been tried during this period and has been found to be better, involves the determination for the vented chamber of correction terms which allow for the combined effect of source, microphone, and exhaust ports.

B. Experimental Basis and Method of Calculation

The experimental basis and method of calculation is the same as that described in the preceding section. Measurements are made to determine ξ and θ for two identical vented chambers of different volumes, both with rigid termination. This permits evaluation of the term $\left[1 + \frac{Z_1}{Z_0}\right]^{-1}$ in equation (1) as a complex number $a + bj$ by use of the relationships (7) and (8). (Note that a and b as used here have a different significance from the a and b introduced as working symbols in equation (6).) The correction terms a and b , so determined, can then be used for vented chamber measurements in equation (9) and (10) in place of s and t which are there used. The same calculation procedure can thus be used for both solid and vented chambers and is much simplified. The values found for correction terms for the solid and vented chambers are shown in Table I.

TABLE I
CORRECTION TERMS FOR SOURCE AND VENT IMPEDANCE (1 ATM.)

Frequency Kc	Real		Imaginary	
	s	a	t	b
.2	.88	- .045	.0984	+.03
.3	.86	- .16	.130	-.1134
.4	.87	- .298	.0163	+.0924
.5	.90	- .623	.0333	.0982
.6	.93	-1.226	.034	.3055
.7	.97	-2.86	.052	1.985
.8	.98	+3.612	.0866	7.385
.9	1.038	3.16	.0713	1.366
1.0	1.040	2.643	.0358	0.447

It can be seen that the correction terms s and t for the solid chamber approach unity and zero respectively, as previously noted¹, but deviate from these values sufficiently so that they must be taken into account for accurate results. The correction terms a and b , which account for all acoustic elements in the vented chamber other than the chamber volume and sample, cover a wide range of values and are very sensitive to frequency.

Experimental test of the validity of the calculation method using these correction terms was made by comparing results of measurements on well-defined sound absorbing samples in both the 20cc solid and 20cc vented chambers. The solid chamber results are assumed to be correct, and the criterion of the calculation method is the agreement shown by the vented chamber measurements. The results obtained from such a comparison at 1 atmosphere with a perforated metal plate sample and a fiber glass pad sample are shown in Tables II and III respectively. In both cases, the agreement shown by the imaginary components of acoustic impedance ratio is fairly good, but agreement of the real components is not as good. With the perforated plate sample, agreement of the real components is erratic and poor except at the two highest frequencies. The fiber glass pad sample shows considerably better and more consistent agreement at frequencies above 0.5 kc, and is probably a better acoustic reference standard than the perforated metal plate which is so constructed that complex resonance effects may be introduced by the air space behind the top perforated surface.

TABLE II
SPECIFIC ACOUSTIC IMPEDANCE RATIO OF PERFORATED PLATE SAMPLE (1 ATM)

Frequency (Kc)	Real (R)		Imaginary (X)	
	Solid	Vented	Solid	Vented
.2	3.89	-51.4	-42	-16.8
.3	3.36	-16.4	-28.2	-29.0
.4	0.67	+12.8	-21.4	-22
.5	1.16	- 0.81	-16.9	-19.8
.6	0.865	+ 1.52	-13.1	-15.3
.7	0.96	+14.7	-11.6	-15.1
.8	1.39	- 0.50	- 9.64	-11.0
.9	1.40	1.07	- 8.65	- 8.2
1.0	0.98	0.85	- 7.2	- 9.5

TABLE III
SPECIFIC ACOUSTIC IMPEDANCE OF FIBER GLASS PAD (1 ATM)

Frequency (Kc)	Real (R)		Imaginary (X)	
	Solid	Vented	Solid	Vented
.2	1.40	-6.7	-14.1	-11.7
.3	.99	.30	- 9.7	- 8.6
.4	1.05	.44	- 7.3	- 6.7
.5	1.30	.51	- 5.9	- 4.0
.6	1.18	.65	- 5.1	- 4.9
.7	1.07	.60	- 4.4	- 4.2
.8	.99	.59	- 3.8	- 3.9
.9	.84	.46	- 3.35	- 3.4
1.0	.69	.61	- 3.20	- 3.1

Comparison of results obtained in solid and vented chambers on the fiber glass pad sample was also made at 200 psi and is shown in Table IV. For this purpose, it was necessary to make preliminary determinations of s and t , and a and b correction terms at this pressure by the procedure previously described.

The values so obtained are given in Table V. The agreement shown between solid and vented chamber values in Table IV is again fairly good for the imaginary values as it was at 1 atmosphere. The real values obtained for the vented chamber are encouraging in that they are at least all positive at 0.5 kc and above and are in agreement with the solid chamber values within a factor of two on the average. Although better agreement might be obtained, it is considered to be sufficiently good to justify the adoption, for the present, of the calculation method discussed. Further tests on other sound absorbing materials should serve to show whether at a given frequency there is a consistent difference between values for the solid and vented chamber, in which case a correction factor could be applied to the latter.

For future work, the possibility of using a chamber vented downward through a single port located at the center of the grain has been considered. This will not be tested until the performance of the present chamber in active tests has been more completely studied, but it is possible that such a vented chamber design would permit better agreement to be obtained between solid and vented chamber results.

C. Application of Method to Burning Propellant

The active shot tests made during this period have involved the recording of either microphone voltage or microphone signal phase angle relation to the driver

TABLE IV
SPECIFIC ACOUSTIC IMPEDANCE OF FIBERGLASS PAD (200 psi)

Frequency (Kc)	Real (R)		Imaginary (X)	
	Solid	Vented	Solid	Vented
.2	1.71	3.39	-17.5	-26.7
.3	4.05	-.87	-12.5	-12.4
.4	.006	-.731	- 8.5	- 8.1
.5	.25	.37	- 6.9	- 7.0
.6	.22	.25	- 5.2	- 5.9
.7	.35	.17	- 4.6	- 5.1
.8	.05	.09	- 4.4	- 6.6
.9	.27	.09	- 4.2	- 3.8
1.0	.09	.20	- 3.4	- 3.2

TABLE V
CORRECTION TERMS FOR SOURCE AND VENT IMPEDANCE (200 psi)

Frequency (Kc)	s	Real		Imaginary	
		a	t	b	
.2	1.04	- .061	.207	- .148	
.3	.88	- .149	.285	.0685	
.4	.93	- .265	.0168	.0644	
.5	.93	- .546	.0168	.0262	
.6	.85	-1.109	.0742	.162	
.7	.89	-2.166	.149	.895	
.8	1.049	-5.58	.0715	5.86	
.9	1.208	6.0	.116	2.30	
1.0	1.09	2.6	.0073	.521	

current separately in individual runs. For both types of recordings, the microphone signal was passed first through the one-third octave filter of the B & K AF spectrometer and was subsequently recorded at high chart speed on the B & K RMS Level Recorder for voltage. For phase angle recording, this signal was lead to the Ad-Yu phase meter, and the output of the latter, reduced in voltage level with respect to ground by a differential amplifier, was recorded on a Sargent Model MR Recorder.

Both types of recorded measurements have operated satisfactorily and the equipment continues to show good ability to withstand and function despite the severe conditions of propellant combustion. The active shots have however, failed to yield the information required for calculations of acoustic impedance of the burning propellant surface. Two main difficulties have been responsible:

1. Effect of Pressure Surge on Driver Output

The propellant combustion in the present chamber produces an initial sudden pressure surge and sustained pressure differential between inside and outside of the chamber of approximately 2 psi during combustion.

In previous work the amount of venting and microphone characteristics were selected and adjusted so as to be able to function under these conditions, and it was assumed that the conditions established would also permit proper driver operation. This assumption was shown to be erroneous by an experiment in which the driver output was pulsed at one-second intervals during the 4 to 5 second burning period. The result obtained indicated the need to increase the size of small holes that permit equalization of pressure on both

sides of the driver diaphragm. Before this change, the driver output was drastically reduced during combustion, and hence, the recordings of microphone voltage made previously did not give meaningful results. The alterations made in the driver diaphragm will eliminate this source of error in future work.

2. The Effect of Combustion Noise

The magnitude of combustion noise and the extent to which it interferes with the impedance measurements has been discussed in previous reports. The spectrum of combustion noise under the conditions of our measurements has not been determined, but measurements at 500 and 800 cycles/second with a one-third octave filter on the microphone output have shown an intensity of noise passed by the filter equal to about 20 percent of the input intensity. Some improvement in this signal-to-noise ratio was made during this period by the construction and installation of a shorter source tube connecting the driver with the sound chamber. A reduction in the length of this source tube by $1 \frac{3}{8}$ inches has had the effect of doubling the sound input intensity in the chamber, while causing a negligible change in the source impedance.

Despite this favorable change, the combustion noise remains a major source of difficulty, and recent work indicates that filters are needed which will pass a narrower band of combustion noise frequencies near the measuring frequency. Combustion noise, if low in intensity relative to the driver signal does not cause too serious an error in ξ and can be separately measured and corrected for; but its affect on the phase angle measurement is much more serious since it is variable and out of proportion to the amount of combustion noise and is not easily amenable to corrections.

Tests are currently being conducted using the General Radio Type 736A Wave Analyser to adapt its 8-cycle band pass filtering system to the requirements of this work. This system is expected to reduce interference of combustion noise in both intensity and phase angle measurements to an acceptable level. When it has been installed, active tests will be resumed to obtain the data needed for acoustic impedance measurement of the burning propellant surface.

III. SUMMARY

A method for treatment of data obtained in a vented Mawardi Method sound chamber that is suitable for propellant studies has been developed and tested on passive samples which adequately allows for the effects of source impedance and of the vents and gives results in moderately good agreement with those obtained for the same samples in the solid chamber.

Tests on burning propellant have shown the need for a minor modification of the sound driver used which will allow it to function better during sample combustion, and for the use of a more discriminating filter on the microphone output to sufficiently reduce the interference of combustion noise during active shots. Reduction in length of the source tube between driver and chamber has resulted in doubling sound intensity in the chamber.

IV. FUTURE WORK

During the next quarterly period, efforts will be concentrated on selection and putting into service of a better narrow-band filter to reduce to a minimum the interference of combustion noise with the desired acoustic impedance measurements. Testing of the General Radio Type 736-A Wave Analyzer for this purpose will be continued.

After better filtering has been achieved, active shots at single frequencies will be resumed and recordings made in each of both sound intensity and phase angle. These tests will be made first with 1-inch square samples of the single propellant studied thus far, an 82 percent loaded polyurethane propellant, and if successful, will be continued on 2-inch square full size samples of the same propellant. These tests will then be followed by similar measurements on a variety of other propellant compositions.

V. NOMENCLATURE

- A = area of specimen, cm^2 .
- a, b, s, t = impedance equation constants.
- c = velocity of sound.
- d = specific acoustic impedance ratio of solid chamber.
- f = frequency.
- j = $-\sqrt{-1}$.
- P = pressure.
- V = volume of cavity.
- E = microphone signal voltage.
- Z_c, Z_1 = chamber impedance.
- Z_o = source impedance.
- α = ratio of chamber volumes V_1/V_2
- γ = ratio of specific heats.
- ρ = density of air, g/cm^3 .
- ρ_c = characteristics impedance of a plane wave.
- θ = phase angle difference = $\theta_1 - \theta_2$.
- ξ = ratio of microphone voltages.

VI. REFERENCES

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